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Title: Reaction-in-Flight Neutrons and the Stopping Power in Cryogenic NIF Capsules

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Reaction-in-Flight Neutrons and the Stopping Power in Cryogenic NIF Capsules

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ABSTRACT

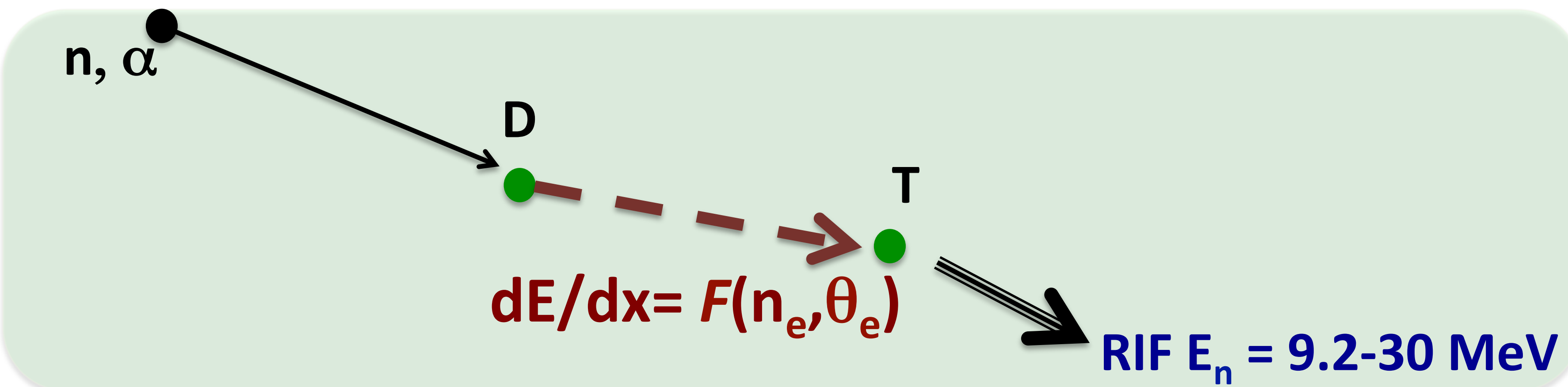
Recent experiments in cryogenic DT capsules at the National Ignition Facility (NIF) observed high-energy reaction-in-flight (RIF) neutrons via threshold (> 15 MeV) neutron reactions on thulium foils. This represents the first measurements of RIF neutrons in inertial confinement fusion plasmas. RIF neutrons are produced by a two-step process. In the first step, a primary 14.1 MeV DT neutron knocks a triton or deuteron up to a spectrum of energies from 0 to more than 10 MeV. In the second step, the energetic knocked-on ion undergoes a DT reaction with a thermal ion, producing a neutron above the primary 14 MeV peak. Transport and energy loss of the knock-on ions inducing the RIF reactions directly affect the RIF production rate, and RIF measurements can be used to determine the stopping power for charged particles in the plasma. Here we present the formalism for extracting the stopping power from the measured RIF signals. We find that the stopping power extracted from these measurements is consistent with a strongly coupled quantum degenerate plasma for the high-density cold fuel surrounding the hotspot of the compressed capsule. These RIF measurements represent the first determination of stopping powers in strongly coupled plasmas.

Outline

- Reaction-in-flight (RIF or tertiary) neutrons and their relation to stopping powers
- Why NIF cryogenic capsules probe stopping powers in an unexplored regime
- The Reaction-in-flight experiments at NIF
- Theoretical analyses and implications of the measurements
- The evidence that the cold fuel in NIF capsules is moderately-strongly coupled and degenerate
- New constraints on stopping power models

RIF production is determined by the fluence of knock-on ions in the plasma

- Reaction-in-flight (tertiary) neutrons require three successive reactions
- Primary neutrons from a DT reaction knock ions up to MeV energies to produce DT reactions out of equilibrium, and, thus, produce super-thermal neutrons



- dE/dx changes the shape and the magnitude of the knock-on fluence

RIF production is directly affected by the stopping power in the plasma

Stopping Power Models

In weakly coupled plasmas there are a number of accurate stopping models $\Gamma = \frac{Ze^2}{R_W \theta_e} \leq 0.1$

Brown, Preston, Singleton (BPS) (Dimensional continuation)
Physics Reports 410 (2005) 237–333

Maynard-Deutsch (MD) (RPA and detailed extensions)
J. Physique 46 (1985) 1113-1122

Zwicknagel (Detailed quantum many-body simulations)
Physics Reports 309 (1999) 117

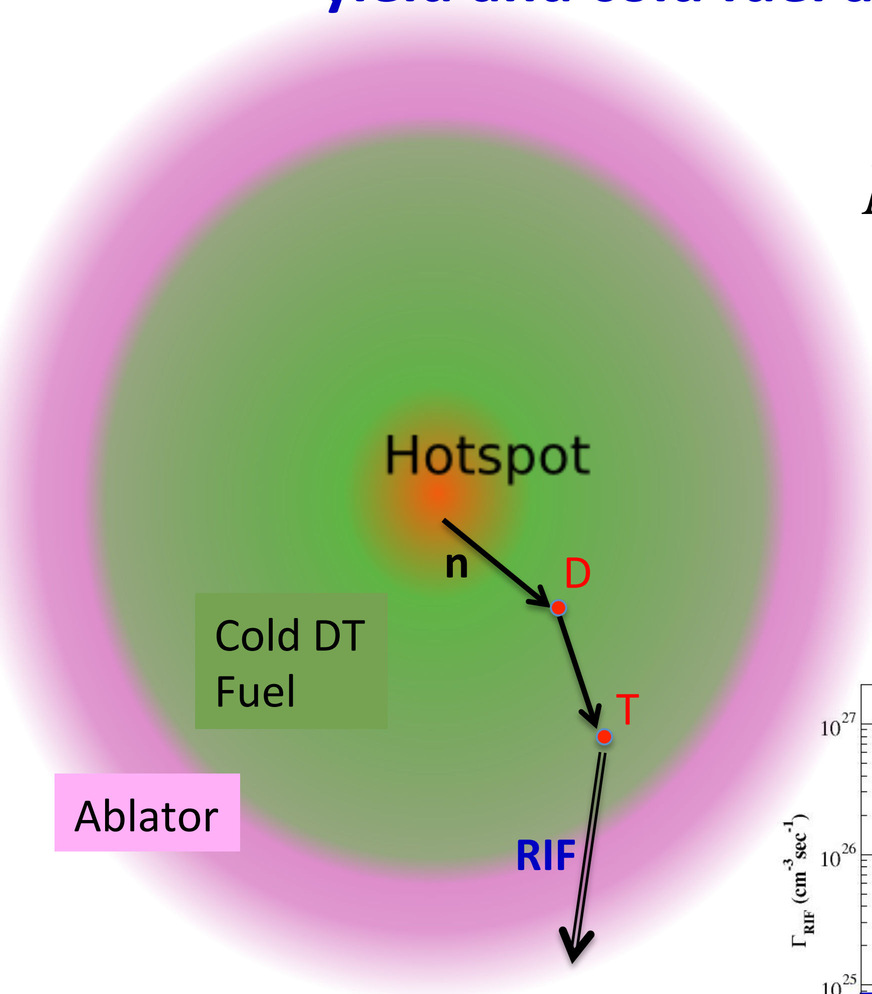
MD and BPS are numerically identical at weak coupling *(LA-UR 13-22639)*

In strongly or moderately coupled plasmas
The situation is unclear and the models typically don't agree $\Gamma = \frac{Ze^2}{R_W \theta_e} > 0.2 - 0.3$

Maynard-Deutsch
Li-Petrasso
Zwicknagel
Grabowski
Corman-Spitzer

These models have extensions to the strong coupling limit
Some can handle electron degeneracy
NONE have been tested experimentally

Cryogenic NIF capsules achieve sufficient primary neutron yield and cold fuel areal density to produce RIFs

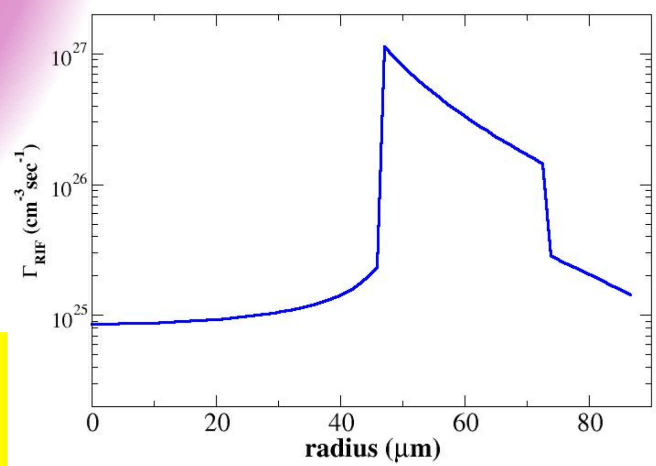


$$N_{RIF}^{Total} = N_{14} \langle \rho R \rangle_{DT} \int \frac{d\tilde{\psi}_{ko}}{dE_{ko}} \sigma_{DT} \, dE_{KO}$$

$\sim 10^{15}$-10^{16} $\quad$ $\sim$ 850 mg/cm^2

Knock-on fluence

$$\frac{d\tilde{\psi}_{KO}}{dE_{KO}} \propto \frac{1}{dE/dX}$$



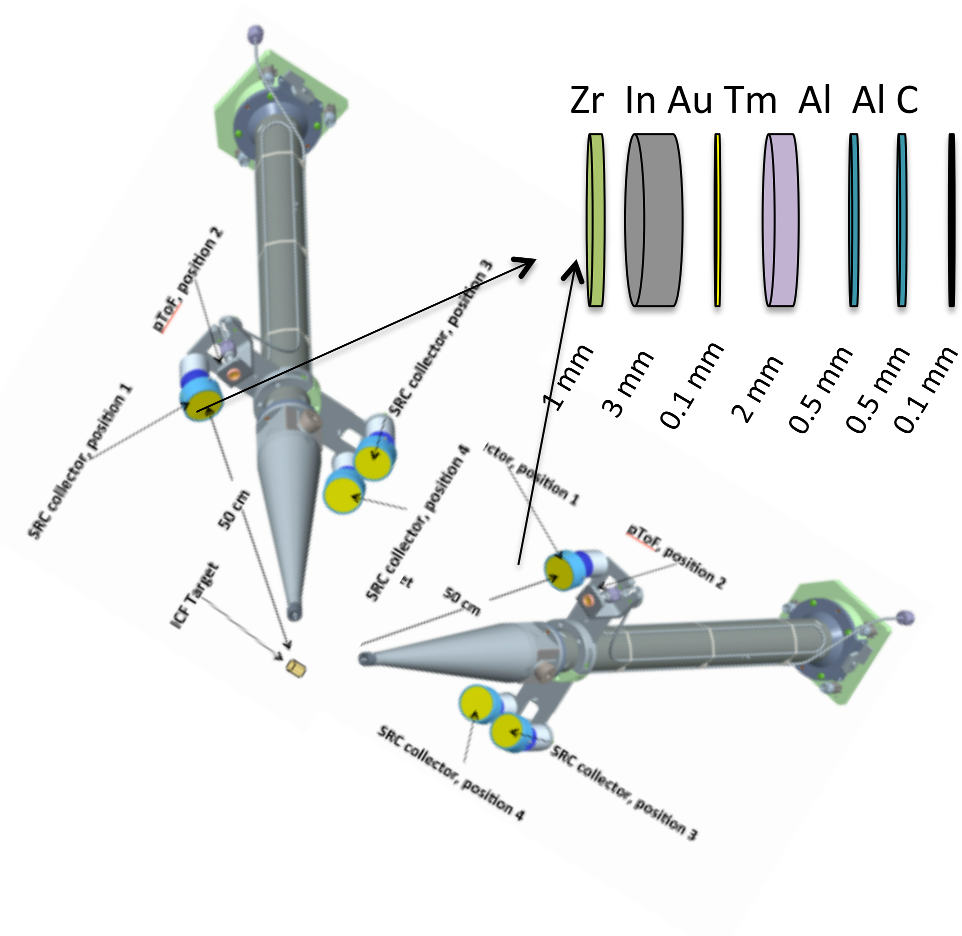
RIFs require high a density DT plasma and are dominantly born in the dense cold fuel in NIF High Foot capsules

Hotspot: $\theta \sim 4$ keV, $\rho \sim 36$g/cm^3

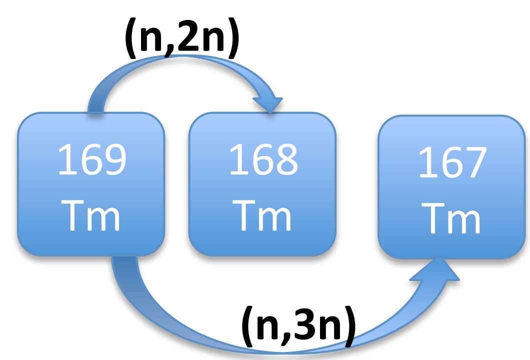
Cold fuel: $\theta \sim 0.2$ keV, $\rho r \sim 850$mg/cm^2
$\Gamma \sim 0.5$

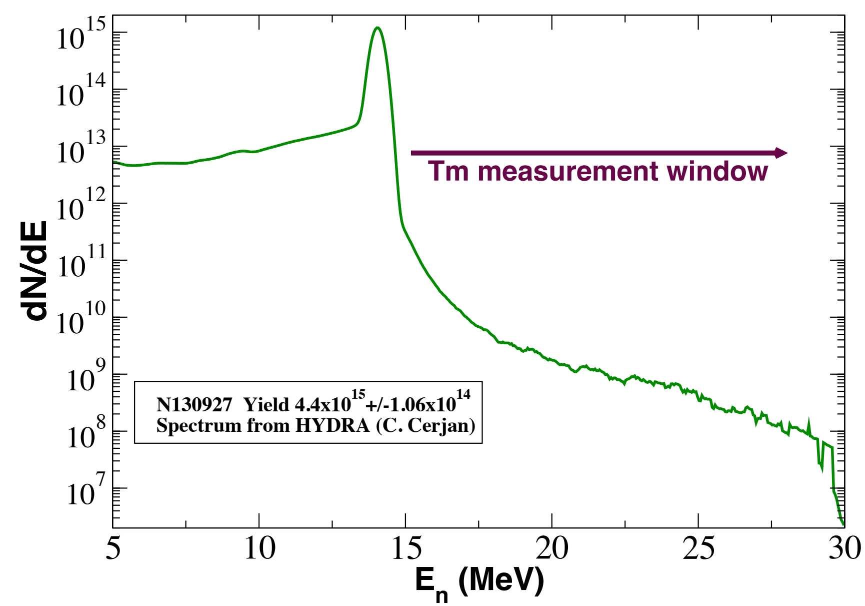
RIF detection was achieved at NIF by detecting neutrons with energies above 15 MeV via neutron activation of thulium foils

RIF setup:
One 2 mm (now 0.5 mm) Tm and one 100 µm Au foil 50 cm from TCC, with 1 on the equator, and 1 on pole.

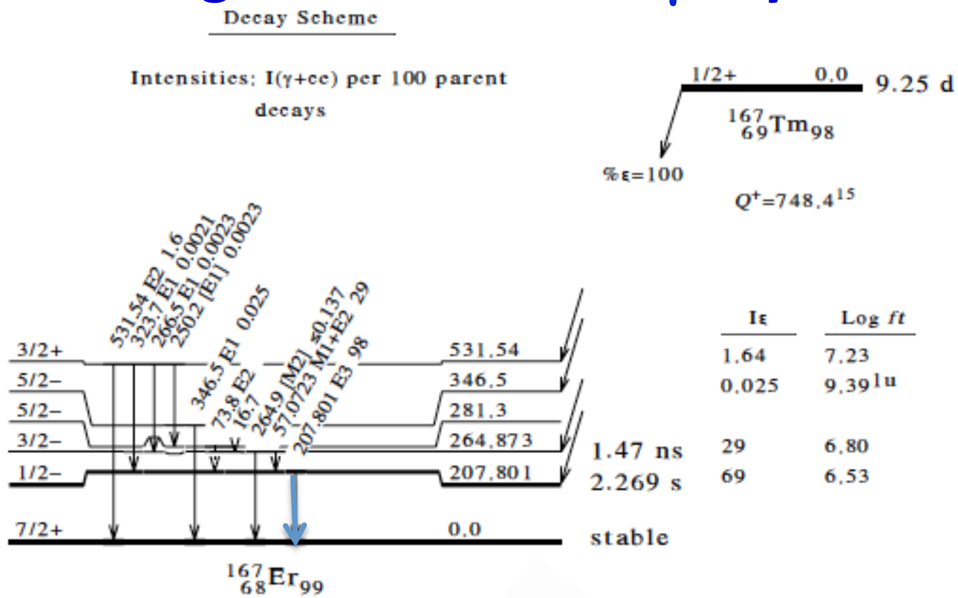


$^{169}Tm(n,3n)^{167}Tm$ E_{Th}=15 MeV

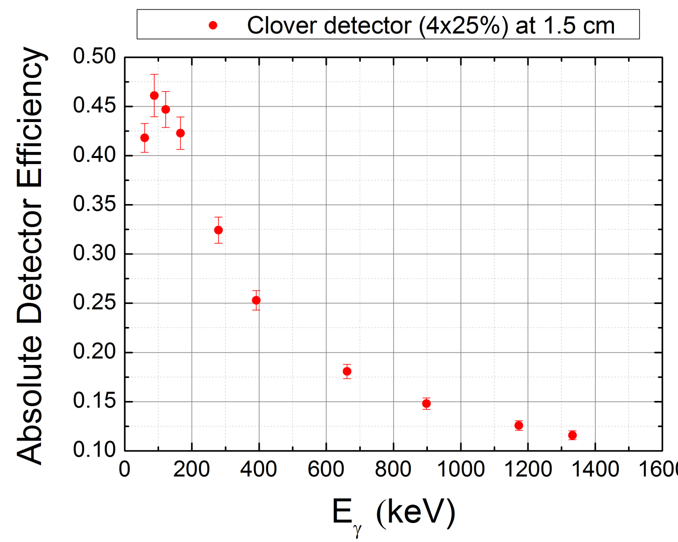


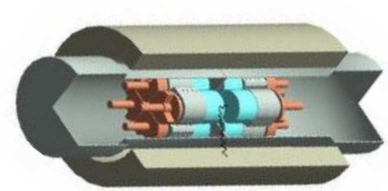


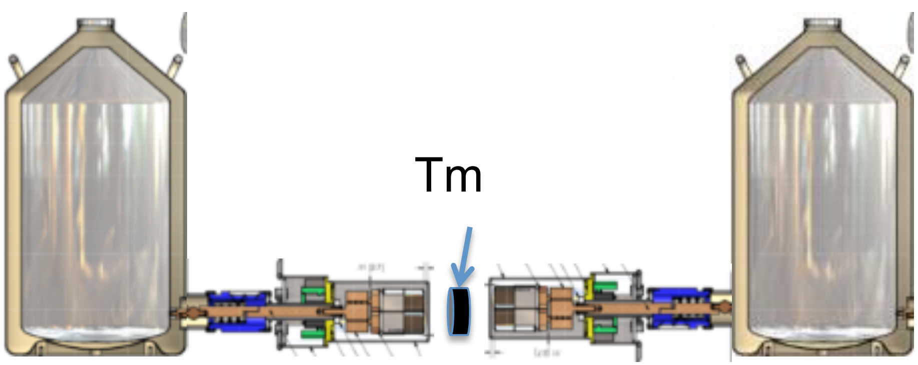
RIF signal is a 208 KeV γ-ray from the decay of ^{167}Tm($T_{1/2}$=9.25 days)



Use of the Los Alamos HPGe 4π clover detector made detection of this line in the huge background of gamma-rays from the decay of ^{168}Tm possible

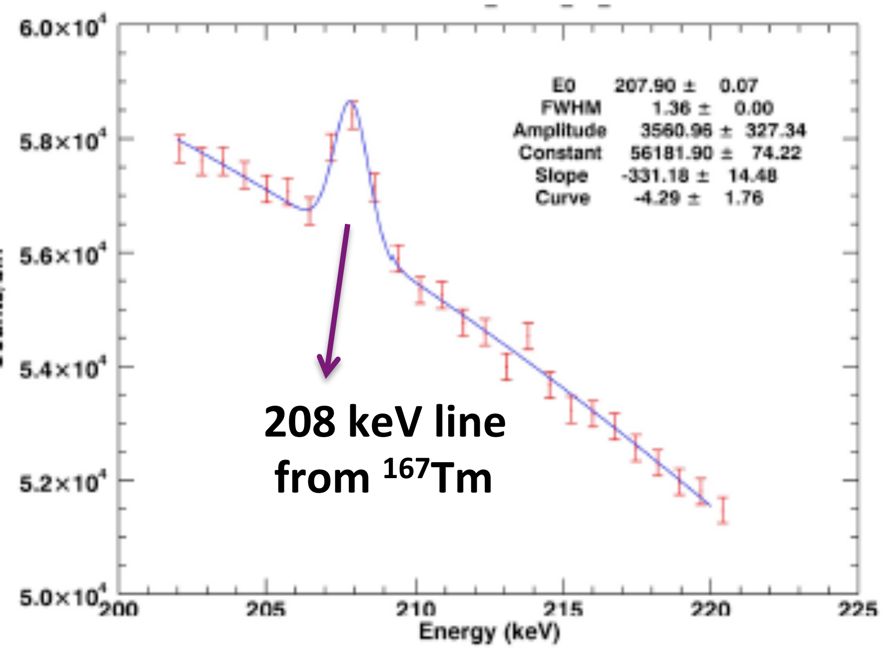






Two highly efficiency clover HPGe detectors
Each clover consists of 4 Ge crystals
Active 4π NaI(TI) Compton Suppressor

Measured ^{167}Tm/^{168}Tm signals on High Foot Shots are ~10^{-5}, which implies a RIF/Total neutron ratio of ~10^{-4}



2mm (2013) vs 0.5 mm (2014) foils
=> uncertainty 37% vs 15%

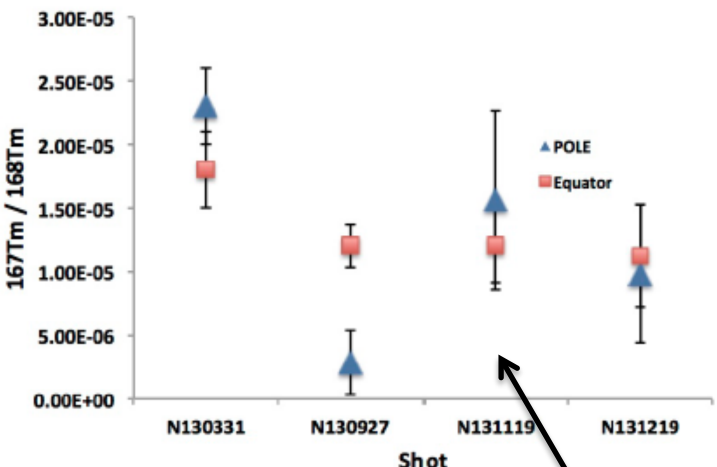
First RIF observation:

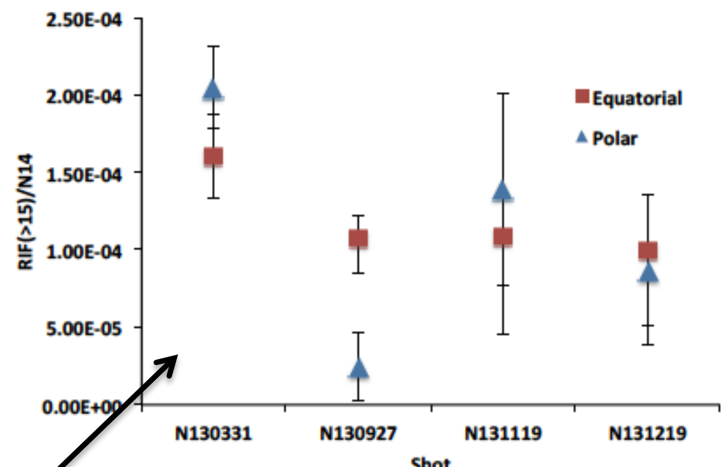
^{167}Tm/^{168}Tm = 2x10^{-5} +/- 0.74x10^{-5}

Recent RIF observation:

^{167}Tm/^{168}Tm = 1.7x10^{-5} +/- 0.24x10^{-5}

Thin foil measurements place strong constraints on the stopping power in the dense cold fuel

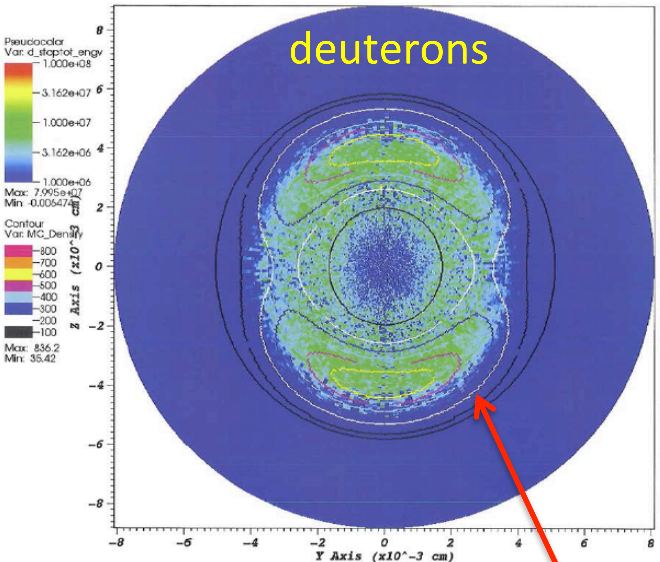


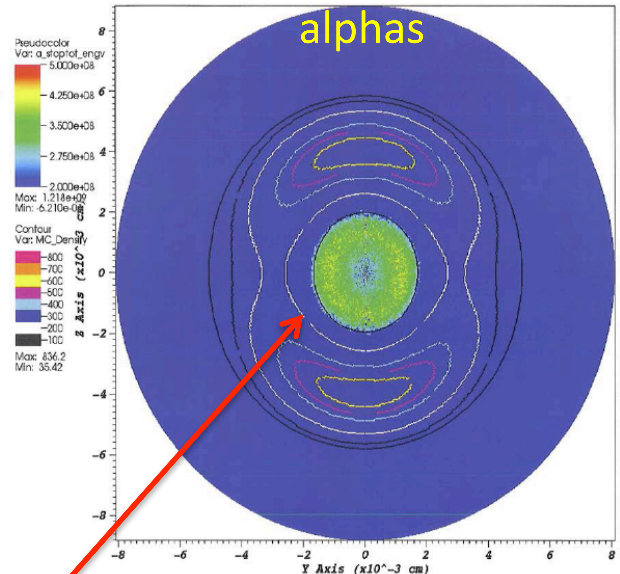


Thick foil results

Extracting the stopping power from the higher precision thin foil RIF measurements

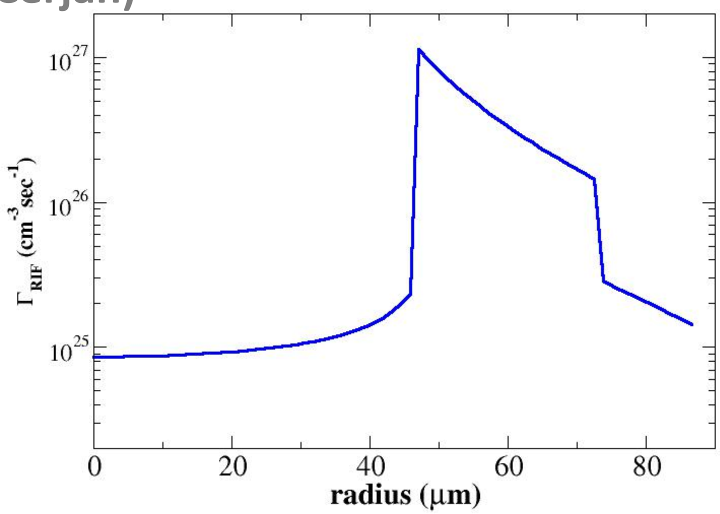
The knock-on D and T ions are dominantly produced in the Cold Fuel So RIFs probe the Cold Fuel stopping





The position of knock-on deuterons versus alphas energy deposition as predicted by HYDRA

(C. Cerjan)

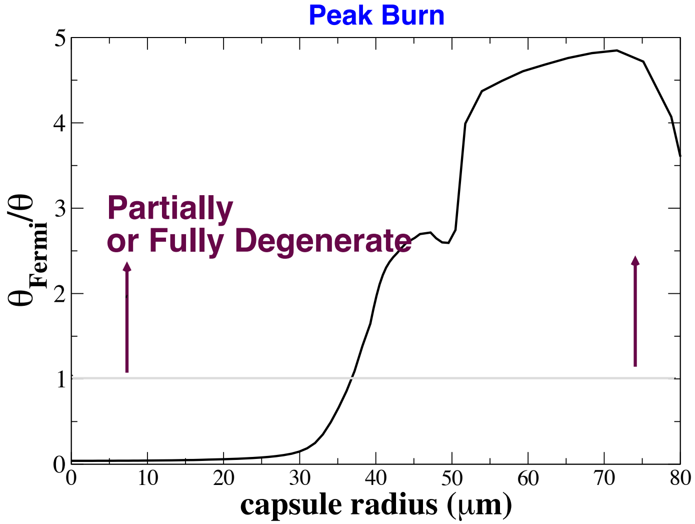


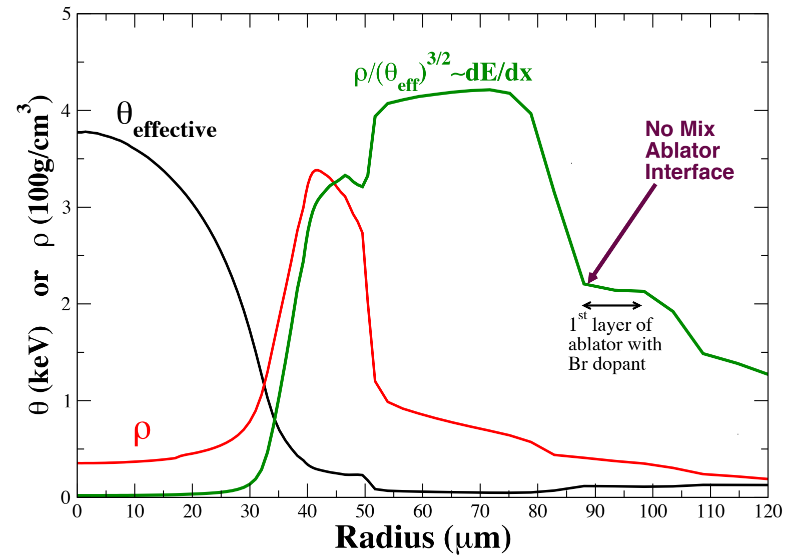
RIFs also dominantly produced in the cold fuel

- as predicted by CPT-Burn code
- in approximate agreement with HYDRA

Knock-on D & T fluence measures dE/dX in the dense strongly-coupled cold fuel

Strong coupling and degeneracy of the Cold Fuel has a significant impact on the transport of the charged particles





$$\frac{dE}{dx} = -\frac{4\pi Z^2 e^4}{m_e V_p^2}\left(\frac{n_e}{\theta_e^{3/2}}\right) G(y)\ln(\Lambda_e)$$

$$\text{degenerate } \theta_e \rightarrow \theta_e^{effective} = \frac{3}{5}\theta_{Fermi} F(\theta)$$

$$\frac{n_e}{(\theta_e^{eff})^{3/2}} \sim \text{constant}$$

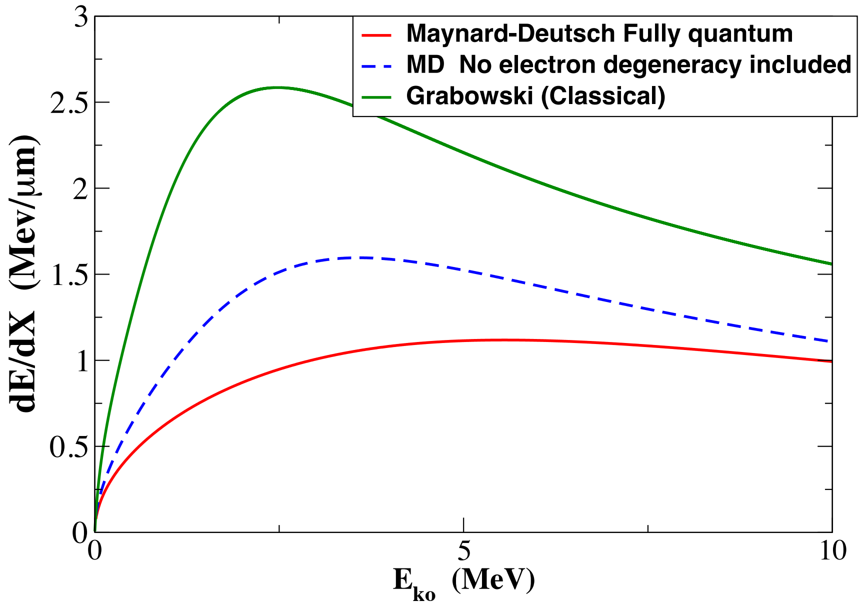
$$\theta_e^{eff} > \theta \Rightarrow \frac{dE}{dx}\downarrow$$

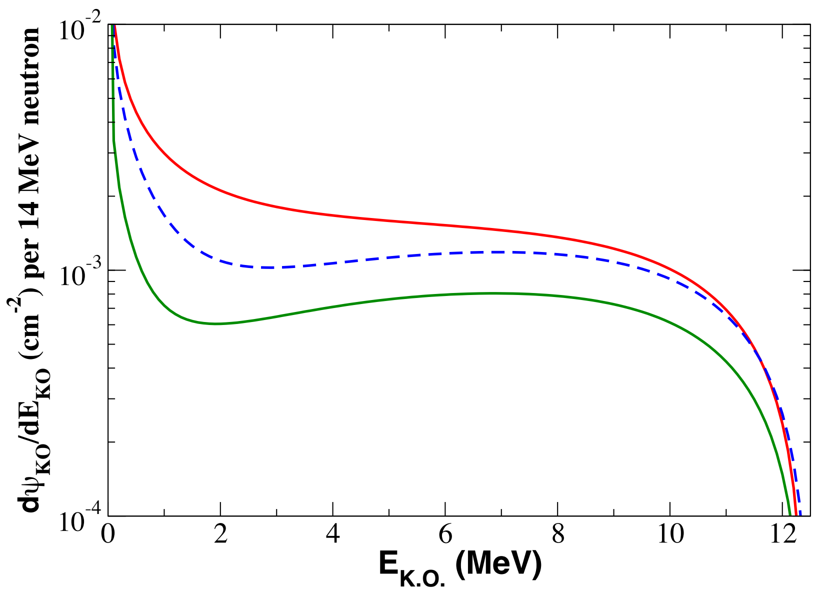
Cold Fuel is Moderately –Strongly Coupled

$$\Gamma = \frac{Ze^2}{R_W \theta_e} \approx 0.5$$

Many stopping powers break-down under these plasma conditions, e.g., BPS

Quantum effects, including the electron degeneracy in the cold fuel, affect the stopping and, hence, the knock-on fluence

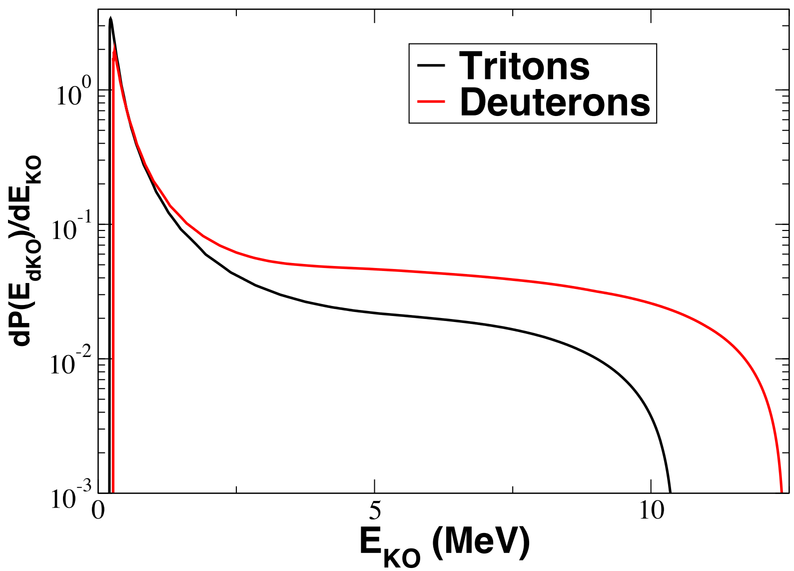




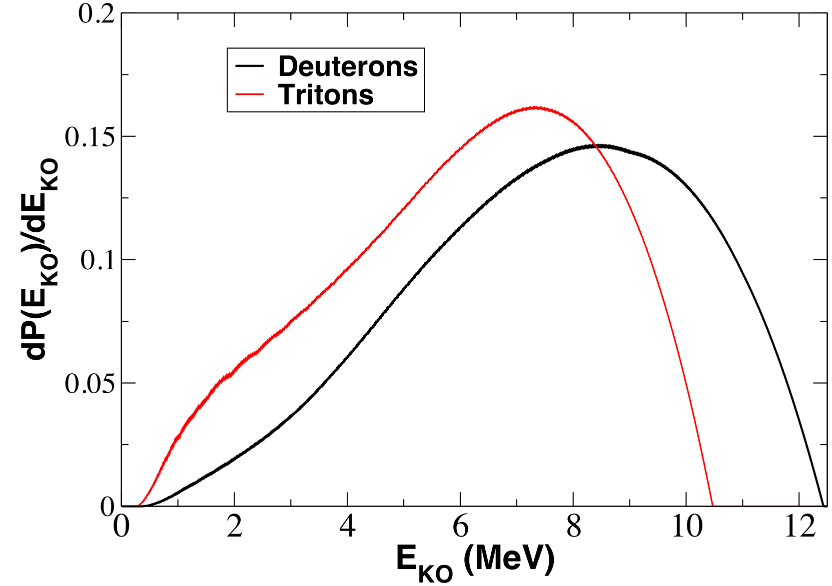
- Quantum effects lower the stopping power by about a factor of two
- The degeneracy of the electrons further lowers stopping
- Electron degeneracy also changes the shape of the stopping and knock-on fluence

The Tm RIF measurements probes knock-on over a range of energies ~0.2-12.5 MeV, with a weighting toward higher energies

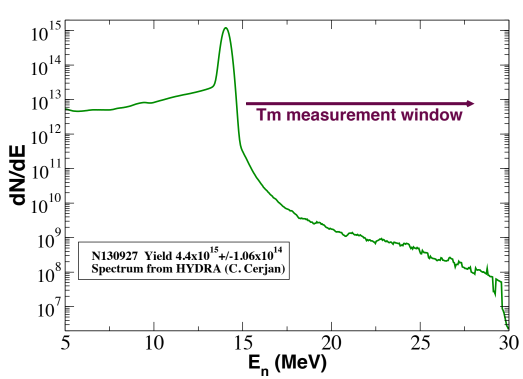
Probability of a given K.O. energy producing the RIFs If the Tm cross section were flat



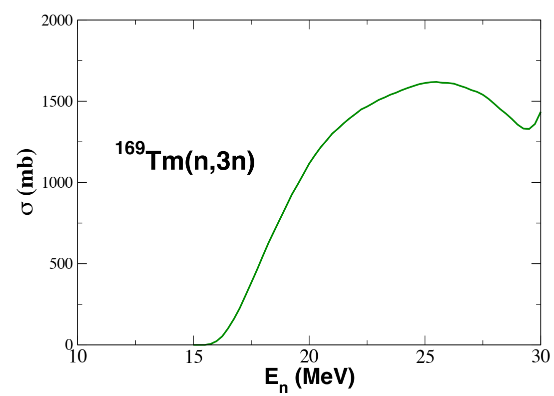
Probability of a given K.o. energy producing the RIFs for the Tm(n,3n) diagnostics



RIF spectrum peaks at low energies

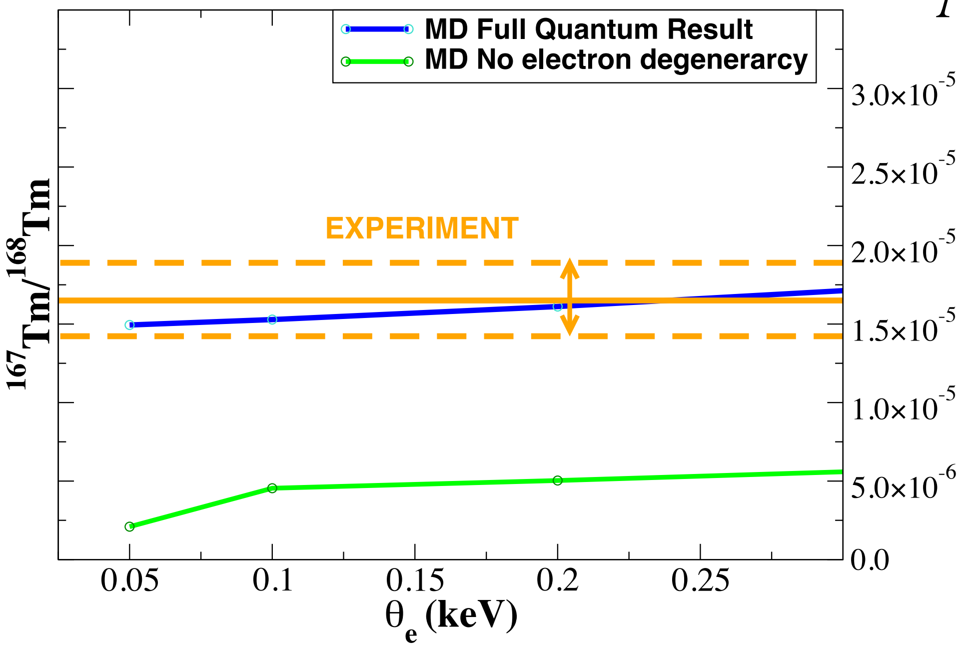


RIFs contributing to Tm <En>~21 MeV



RIF Measurements rule out stopping models for non-degenerate plasmas
The measurements require that the Cold Fuel is a Quantum Degenerate System

$$N_{RIF}^{Total} = N_{14} \langle \rho R \rangle_{DT} \int \frac{d\tilde{\psi}_{ko}}{dE_{ko}} \sigma_{DT} dE_{KO}$$



For the theoretical analysis of RIFs:

- CF <ρr> form the DSR and NI
- N_{14} yield form nTOF and activation
- C. Cerjan runs the Springer-Cerjan consistency analysis
- LANL runs CPT-Burn (a RIF centric code)
- Cross compare both theories to ensure overall consistency

1. ^{167}Tm/^{168}Tm =1.7(+/-0.24)x10^{-5} => RIFs/Total ~ 1.5x10^{-4}

2. Electron degeneracy lowers the stopping power and enhances the RIF production

3. RIF measurements require a quantum degenerate electron plasma in the cold fuel

4. Consistent with HYDRA and CPT-Burn simulations, wherein the cold fuel is predicted to be degenerate

Rif measurements allow us to discriminate between different stopping models

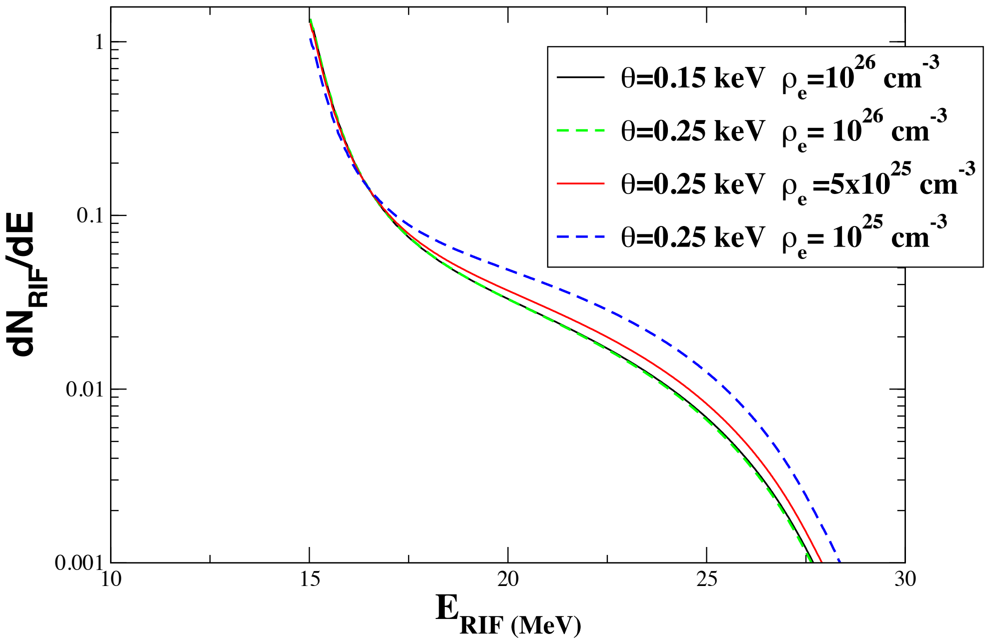
Shot N140306	167/168Tm
Measurement	1.69 (+/-0.24)x10^{-5}
Maynard-Deutsch	1.59x10^{-5}
Li-Petrasso	1.27x10^{-5}
Grabowski	0.89x10^{-5}
BPS	Model breaks-down (Γ~0.5 too large)

- **Similar comparisons are seen of all other shots,**
  - **4 RIF measurements with 2mm foils**
  - **4 RIF measurements with 0.5 mm foils**
  - **2 null tests with high yield, low ρr DT capsules**

- **More recent data also have tight error bars, and are currently being analyzed**

Future directions

Want to measure the shape of the RIF spectrum



Experimental Developments

RIFS by ^{124}Xe(n,3n) via RAGS

Other higher threshold reactions

RIFs by nTOF

- If plasma is fully degenerate, the density determined the RIF spectrum,
  $\rho \sim 10^{26}$ cm^{-3}, $\theta < 0.3$ keV

- If only partially degenerate, the shape changes

- Also looking for evidence for N-N scattering
  - 'kink' in spectrum

Summary

- The first RIF observation in an ICF systems made at NIF by a joint LANL/LLNL team
- The NIF HF platform provides the required areal density and yield to study RIFs
- RIF measurements made by activation of thulium pucks and the observable is the ratio of ^{169}Tm(n,2n)^{168}Tm/^{169}Tm(n,3n)^{167}Tm
- The observed ratio of ^{167}Tm to ^{168}Tm is shot dependent, but is in the range $1\text{-}2\times10^{-5}$

  This corresponds to a ratio of RIF neutrons to total neutrons of about $0.8\text{-}1.8\times10^{-4}$
- The measured RIF ratio has important implications
  - Verified that the assembled cold fuel is a dense quantum degenerate system
  - Discriminates between stopping models
  - Validates the charged-particle transport packages in the burn codes
- A LANL and LLNL team are currently developing an nTOF RIF capability

  Also looking at possible higher threshold Radchem reactions